

Planetary Astronomy

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## INTRODUCTION AND SUMMARY

Planetary astronomy - the study of planetary bodies and phenomena by astronomical remote sensing techniques - has represented a major element of astronomy since the invention of the telescope. Most of the discoveries by Galileo and his successors during the 17th and 18th centuries were in the field of planetary astronomy. In our own century, astronomical observations have provided the basic data, ranging from planetary masses and orbits to the properties of their atmospheres and surfaces, that have made possible the initial spacecraft reconnaissance of the solar system. Even today, in an era of numerous spacecraft missions, astronomical techniques still yield much of the information we have on the physical and chemical nature of planets, satellites, rings, comets, and asteroids. Furthermore, astronomical techniques are providing the opportunity to expand our perspective to embrace the discovery and study of planetary systems orbiting other stars.

The field of planetary astronomy is a subdiscipline of astronomy dealing with observations of the members of our own solar system carried out from ground-based, airborne, and orbiting observatories. It employs many of the same facilities and techniques that are used by other astronomers, spanning the electromagnetic spectrum and encompassing laboratory and computational tools as well as telescopic observations. This field is strengthened by support from two major federal agencies, the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF).

A number of recent discoveries highlight the continuing capability of astronomical techniques to contribute to planetary studies. These include:

- Discovery of the ring systems of Uranus and Neptune in advance of Voyager, and continuing ability to monitor changes in the rings and thereby study ring dynamics and planetary structure.
- Radar mapping of the topography of Venus and identification of volcanoes and rift zones that bespeak an active geology beneath that planet's opaque clouds.
- Discovery of deuterium in the martian atmosphere and use of this isotope as a measure of loss of water from Mars in the past.
- Discovery of numerous atmospheric constituents of Jupiter and Saturn, including organic compounds that record the complex photochemistry in the upper atmospheres of these giant planets.
- Identification of the composition of the surfaces of the satellites of the outer planets, including water ice (frost) on many satellites, sulfur dioxide and hydrogen sulfide on Io, and methane and nitrogen gas on Triton.
- Determination of the radius, mass, density, and surface reflectances of Pluto and Charon, and determination of the structure of Pluto's atmosphere.
- Identification of the wide-spread presence of black organic material on the surfaces of many satellites, comets, and asteroids throughout the outer solar system.
- Identification of the compositions of many asteroids with well-known meteorite types (including the discovery of iron asteroids), and determination of a compositional gradient across the asteroid belt that is a remnant of the original compositional gradient in the solar nebula.

In this report we profile the field of planetary astronomy, identify some of the key scientific questions that can be addressed during the decade of the 1990's, and recommend several facilities that are critically important for answering these questions. The most important of these facilities for planetary astronomy, prioritized according to their cost within the "space-based" and "ground-based" categories, are:

Major Space-based:	1. Space Infrared Telescope Facility (SIRTF)
Moderate Space-based:	1. Stratospheric Observatory for Infrared Astronomy (SOFIA) 2. Search for Other Planetary Systems from Earth Orbit
Small Space-based:	1. Orbiting Planetary Telescope/Planetenteleskop (OPT/PTEL)
Major Ground-based:	1. Infrared-Optimized 8-meter-Class Telescope
Moderate Ground-based:	1. none
Small Ground-based:	1. Arecibo Radar Upgrade 2. Astrometric Facility for Planet Detection

These facilities, which will complement and extend those already available to the United States astronomical research community, will ensure U.S. leadership in astronomy into the next millennium and will enable planetary astronomy to continue as a major component of our effort to understand the universe and its origin and evolution.

## STATE OF THE PROFESSION

Planetary astronomy has contributed greatly to our current understanding of the solar system. Today, both astronomical and spacecraft studies, together with laboratory research on meteorites and lunar and martian samples, constitute an essential element of our quest to understand the solar system.

During the first half of the 20th century, planetary astronomy in the United States declined to the level of a minor branch of astronomical research, but a strong resurgence in this field began in the early 1960's as NASA initiated its program of lunar and planetary exploration by spacecraft. Not only did the need exist to learn as much as possible about the potential targets of spacecraft missions, but NASA's exploration goals also rekindled scientific interest in the planets. NASA, with its charter to explore the planets, took the lead in stimulating and supporting planetary astronomy. In the 1960's, it established a grants program, supported graduate and postdoctoral students, and funded the construction of three large telescopes for planetary work at the Universities of Arizona, Texas, and Hawaii. In the 1970's, NASA built the 3-meter national Infrared Telescope Facility (IRTF) in Hawaii and contributed to the development and operation of the Arecibo planetary radar facility in Puerto Rico.

These efforts together with the exciting new research opportunities stimulated a resurgence of planetary astronomy. Today planetary studies represent a significant and healthy component of astronomical research, with between 200 and 300 active planetary research astronomers in the United States. The great majority of these individuals draw at least partial support from federal grants; about 100 are Principal Investigators (P.I.s) in NASA's Planetary Astronomy Program, and about 15 more are P.I.s in the NSF planetary program. During the 1980's, an average of between 5 and 10 students were granted doctoral degrees in this field each year, which represents a significant drop from the previous decade. This Panel estimates that planetary astronomers now represent approximately 15 percent of research astronomers in the U.S. and somewhat more than 25 percent of U.S. planetary scientists (most of the remaining planetary scientists in the U.S. have backgrounds in the Earth sciences or physics.)

The primary professional society representing planetary astronomy is the Division for Planetary Science (DPS) of the American Astronomical Society, with a membership of about 700, including nearly 100 members outside the U.S. Typically annual DPS meetings attract 400 registrants, and approximately 300 individual papers are presented. The U.S. planetary science community also has its own journal, *Icarus*, published in affiliation with the DPS.

Throughout the 1980's, the combined annual budget for NASA and NSF grants programs for planetary astronomy averaged about \$7 million (not including observatory operations). Currently, approximately half of these research funds are expended for studies of primitive bodies such as comets and asteroids. The outer planets and their satellites account for another 25 percent, with the balance devoted to studies of the inner solar system, instrument development, and the search for other planetary systems.

Approximately half of the U.S. planetary astronomers are optical/infrared observers. We estimate that these observers are granted about 600 nights (6,000 hours) per year on the 15 or so U.S. telescopes with apertures of 2 m or larger. This includes 50 percent of the time on NASA's 3-meter IRTF, more than 20 percent each on the University of Hawaii's 2.2-meter and the University of Texas' 2.7-meter and 2.1-meter telescopes, and less than 5 percent on each of the other telescopes in this class. During the 1980's, less than 3 percent of the time on the major telescopes of the National Optical Astronomy Observatories was assigned to planetary work. Other planetary

observers use the Kuiper Airborne Observatory (KAO), International Ultraviolet Explorer (IUE), Arecibo radar, or the Very Large Array (VLA) and various millimeter and submillimeter telescopes.

In order to improve our understanding of the planetary profession, the Panel carried out a demographic survey of members of the DPS in 1989. We found that about half the professional membership (student members were not included) of the DPS categorize themselves as "planetary astronomers", and that this group consists of about 90 percent males and 10 percent females. Typically a planetary scientist works primarily on planetary studies; more than 60 percent of respondents stated that they spend more than half their time on planetary research, and 40 percent stated that they devote all of their time to this activity. Half of the respondents work for universities, 30 percent for government labs (including JPL), and 20 percent for other organizations. About 75 percent draw a portion of their salaries from grants ("soft" money), with more than 25 percent fully dependent on "soft" money.

The soft-money planetary scientists are about equally distributed over all age groups. A surprising number of even the most senior people in the field draw all or most of their salary from grants. Consequently, planetary astronomers are highly vulnerable to fluctuations in federal funding, and many scientists have preferred to leave the field in the face of apparently arbitrary threats to their core funding. In general, these funding uncertainties have resulted in lowered morale and have discouraged young people from entering the field of planetary astronomy.

While the numbers of planetary astronomers and their funding have generally held level or even declined in the U.S. during the 1980's, this field has been growing elsewhere. During the past decade, planetary science has seen a dramatic resurgence in Europe, parallel to the evolution of this field in the U.S. during the 1970's. We may anticipate a similar growth within Japan during the 1990's. Largely as a byproduct of its own space exploration effort, the U.S.S.R. has maintained a small but highly capable cadre of planetary scientists.

## SCIENTIFIC OPPORTUNITIES FOR THE 1990's

Planetary astronomers study a wide variety of objects and phenomena, using techniques that range from traditional telescopic studies of faint objects to laboratory studies of meteorites and cosmic dust. Generally, however, we can divide this work into efforts to answer two fundamental questions: How did the solar system form; and what can we learn about our own planet Earth by comparative studies of the processes on other planets? These two major themes provide the basis for the discussion that follows.

### Origin and Evolution of the Solar System

#### *Planetary Systems in Formation: Protoplanetary Disks*

It is widely believed that the formation processes that generate stars from the condensation and collapse of interstellar material also are capable of forming planetary systems. The star formation process is discussed in some detail in the report of the Optical/Infrared Panel in Chapter III of this volume. As reported there, recent observational evidence points to the widespread association of disks of gas and dust orbiting young stellar objects. These disks may be the equivalent of the solar nebula out of which our own planetary system formed some 4.5 billion years ago.

An important step toward placing the origin and evolution of the solar system in the context of other planetary systems was the discovery by the Infrared Astronomy Satellite (IRAS) that disks persist beyond the era of star formation and can be found orbiting some main-sequence stars. Particle disks have now been discovered around 150 main sequence stars. While we cannot yet detect planets orbiting other stars, we can begin to study the related properties of these disks, which may be analogous to our own comet clouds, but more populous.

An important problem during the next decade will be to measure properties of the disks such as mass, temperature and albedo distributions, as well as the carbon monoxide/dust ratios. Collisions of planetesimals in orbit around other stars may be expected to generate extended circumstellar dust disks which may be observable in the infrared region of the spectrum. The characterization of circumstellar dust and gas disks around main sequence stars could provide important information on the statistics and evolution of planetary systems. The Space Infrared Telescope Facility (SIRTF) will be an especially powerful tool for the investigation of circumstellar disks.

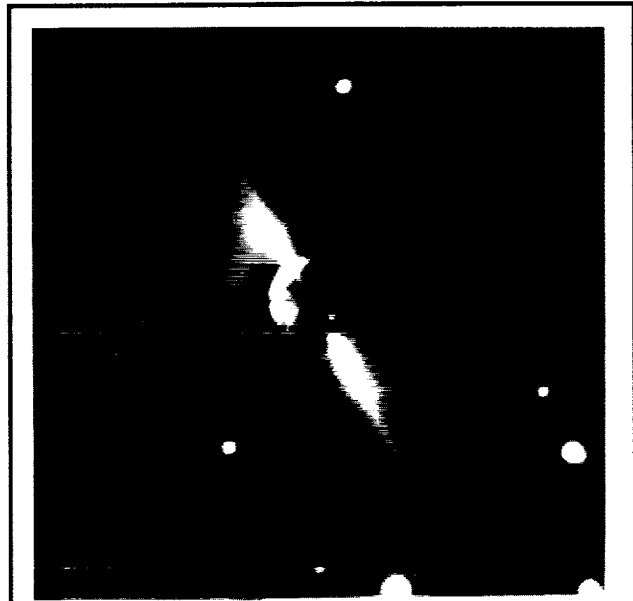
#### *Completing the Inventory of the Solar System*

To understand the origin of our own solar system, it is essential to establish its limits and inventory its contents. The decades of the '70s and '80s were spent in intensive study of the major bodies of the solar system and have greatly enriched our knowledge of their nature. However, we still do not have a complete inventory of all of

the bodies of the solar system, nor of the detailed characteristics of those that have been discovered. Over the past decade, estimates of the mass of cometary material have increased by an order of magnitude, and the prevalence of dark organic material has been established on numerous bodies throughout the system. Today we recognize that the Trojan asteroids (orbiting the Sun at the distance of Jupiter) are as numerous as the asteroids of the main belt, a fact that was unsuspected a few years ago. And there is much yet to be learned, even about the populations of objects in the inner solar system.

Our direct knowledge of the contents of our solar system stops at Pluto's orbit. Information on the mass distribution beyond Pluto is important for understanding both the processes which control planetary accumulation in protoplanetary disks and those which control the dispersal of the disks. Furthermore, the reality of a Kuiper belt of comets beyond Pluto, apparently required to explain the origin of short-period comets, has not yet been observationally established. On a completely different scale, we have identified less than 10 percent of the estimated population of Earth-approaching asteroids. We are unable yet to say whether the observed number is consistent with injection from the 3:1 resonance in the asteroid belt or requires that many such asteroids be extinct cometary nuclei. Thus systematic surveys continue to be of great value.

The technology is ripe to perform much more thorough surveys, particularly in the outer solar system. There have been several estimates of the number and total mass of cometary nuclei in the Kuiper belt, and plausible estimates of the size distribution indicate that the number of such objects detectable with current technology is large. The most complete current survey is to visual magnitude  $V = 22.5$  covering 4.5 square degrees. An all-ecliptic survey to red magnitude  $R = 23$  (and perhaps to  $R = 24$ ) is feasible. This project should be of extremely high importance since the Oort cloud, if it really exists, represents a significant mass. It also validates the concept that comets may be true cosmo-thermometers useful for determining conditions in the early solar nebula. Such a survey would also place tight constraints on the existence of any planets as large as Pluto out to very large distances from the Sun.



A distant analogue of our own planetary system is shown in this coronagraphic photo of Beta Pic. The star is accompanied by a flat disk of solid material with dimensions of hundreds of AU. Advanced infrared instruments (SIRTF, SOFIA, and large ground-based telescopes) will greatly expand our ability to study other planetary systems, especially during their formative periods. *Las Campanas image reprinted by permission from R.J. Terrile (JPL) and B.A. Smith (Univ. Arizona).*

#### *Remnants of Creation: Primitive Material in the Solar System*

The most fundamental property of the members of the solar system, once they are discovered and their orbits determined, is their composition. Many of the most important advances in planetary studies during the '70s and '80s involved the identification of ices and organic materials on many objects, ranging from the moons of Mars to the comets of the distant Oort cloud. These objects preserve relatively pristine material from the time that the solar system formed from the primordial solar nebula.

Preliminary evidence suggests that the low-albedo materials covering (or comprising) comets and some asteroids and planetary satellites consist of macromolecular carbon compounds of low volatility, similar to those materials found in the carbonaceous meteorites. It is of primary importance to establish in detail the connection between the low-albedo materials in the outer solar system and the carbonaceous meteorites, because the chemistry, mineralogy,

and thermal histories of the meteorites are relatively well understood. At the same time, the connections between the organic contents of the comets and the interstellar medium require further elucidation, as the study of pre-solar material proceeds with samples of comets and asteroids (the meteorites and interplanetary dust particles) in the laboratory. These studies will be carried out primarily through infrared, millimeter, and submillimeter spectroscopy, with large aperture ground-based telescopes, supplemented by critical observations that can only be made by the Stratospheric Observatory for Infrared Astronomy (SOFIA) from above the terrestrial water vapor, or by a cryogenic optical system such as SIRTf in deep space.

The most primitive bodies are the comets. Our knowledge of the physical characteristics of cometary nuclei has advanced tremendously during the past decade. We now realize that these bodies are typically irregular in shape, very dark, and spectrally distinct from asteroids. Most are small with dimensions of only a few kilometers, but one much larger object (Chiron) also displays comet-like behavior. Several comets have been observed to be active at heliocentric distances greater than can be explained by a water ice model. Rotational periods are now known for a few comets, and at least one of these (Comet Halley) may be in a complex dynamical state. Most surprisingly, it has been learned that cometary activity is often confined to a small fraction of the total surface of the nucleus.

The chemical compositions of primitive bodies are key indicators of the processes that occurred during the formation of our planetary system, and it is now possible to characterize these compositions by astronomical means. Several key findings of the spacecraft missions to Comet Halley and of the extensive Earth-based observational program demonstrate the high degree of spatial and temporal variability of the composition of gases in the coma. The diversity of chemical species and the complexity of physical phenomena, both on the nucleus and in the coma, require extensive simultaneous measurements using several techniques and a variety of spatial scales in order to properly interpret individual comets and also to place individual comets in the context of the ensemble of comets. A major challenge of the 1990's will be to understand the physical processes that have produced the observed characteristics. In this regard, spectrophotometric observations of dormant comets at large heliocentric distances will be particularly valuable.

Major uncertainties in our current understanding are amenable to resolution in the next decade. For example, the variations from one comet to another in abundance of volatiles relative to water, particularly the dominant volatiles carbon monoxide and carbon dioxide, may be addressed with proposed orbital facilities. Similarly, the abundance of cosmogonically significant but minor constituents such as sulfur, formaldehyde, methane and ammonia, may also be addressed. Elemental and isotopic abundances must also be determined. Elemental abundances will allow us to assess the completeness of our inventory of parent species, while isotopic ratios for certain molecules bear direct cosmogonic significance. Additional new species must be sought, such as the noble gases and complex hydrocarbons, and the heterogeneity of all species within the nucleus must be assessed.

Radar observations have yielded a wealth of new information about the physical properties of several comets and dozens of asteroids. The first direct detection of a cometary nucleus in 1983 was followed by the discovery of large particle clouds associated with Comets IRAS-Araki-Alcock and Halley. The radar signatures of near-Earth asteroids are highly diverse and reveal that a number of these small objects have extremely irregular, non-convex shapes. Radar has also been used to establish the metallic nature of a few asteroids and thus to verify less direct compositional inferences from visible and infrared spectrophotometry. Radar refinement of orbits is important for maintaining the accuracy of both inner-planet and asteroidal ephemerides. This capability is critically important for newly discovered Earth-approaching asteroids, since the detection of radar echoes can guarantee the optical recovery of asteroids on subsequent apparitions.

Many asteroids are compositionally intermediate between the primitive comets and more highly-processed planets and satellites. Spectrophotometric studies have revealed a variety of mineralogical classes, interpreted as representing various degrees of metamorphic and aqueous modifications of original primitive organic material. We have established further that composition is correlated with distance from the Sun, and therefore that the current asteroid population preserves information on the spatial variation of conditions in the solar nebula. However, telescopic studies must be extended to smaller objects and greater distances from the Sun, and also supported by improved laboratory and theoretical developments, before this record of the past can be interpreted with confidence.

A major opportunity for detailed study of primitive bodies will be provided by the 1996 launch of a NASA spacecraft to explore asteroid Hamburga and Comet Kopff. After flying past the asteroid in December 1997, the Comet Rendezvous and Asteroid Flyby (CRAF) spacecraft will match orbits with the comet, which it will study at close range from its arrival in July 2000 until past perihelion passage in December 2002. The spacecraft results will be enhanced and extended to other comets and asteroids through detailed Earth-based observations carried out in parallel with the *in situ* measurements. A number of the new astronomical facilities being considered for the 1990's will directly support - and benefit from - the results of the CRAF mission.

### *An End-Member Planet: Pluto-Charon*

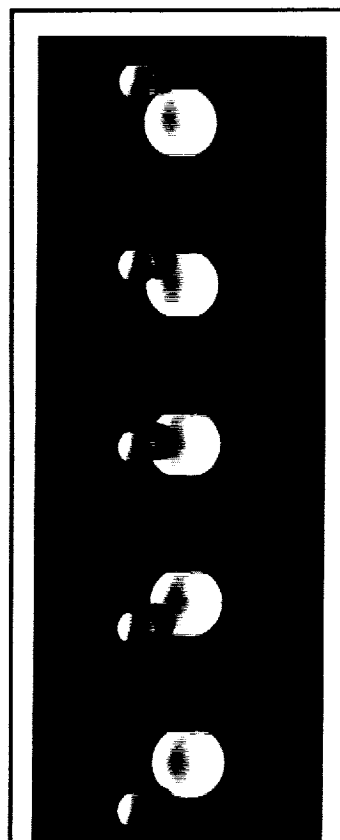
As the most distant known planet, Pluto and its satellite Charon present a unique opportunity to test current models of the formation and evolution of the solar system. Since the Pluto-Charon system has not been visited by spacecraft (nor are there plans to do so), what we do understand about it is based on astronomical observations from the ground, aircraft, and Earth orbit. From these we have a crude albedo map of Pluto's surface and know that its atmosphere contains methane, as well as a heavier gas, probably carbon monoxide or nitrogen. We also know the bulk density of the system is  $2.1 \text{ g/cm}^3$ , which is high enough to imply that Pluto and Charon formed separately in the solar nebula, rather than in a circum-planetary nebula with a subsequent escape into a solar orbit.

But how did Pluto and Charon become gravitationally bound, forming a "double planet"? Are these two bodies composed of the same materials? How does Pluto's atmosphere change diurnally and seasonally, as its solar distance varies from 30 to 50 AU? These questions can be answered by the traditional techniques of planetary astronomy, but implemented with more sophisticated detectors, instruments, and telescopes. The observations needed are: 1) far ultraviolet spectroscopy to detect ionized molecular species in Pluto's upper atmosphere; 2) high resolution infrared spectroscopy to determine the state of the methane and perhaps find additional molecular lines; 3) thermal infrared observations to constrain atmospheric and surface properties; and, 4) stellar occultation observations for determination of Pluto's atmospheric structure. Learning how the observed quantities change as a function of solar distance will be a further diagnostic for inferring more about the system.

### *Are We Alone? Detection and Study of Other Planetary Systems*

Great strides have been made in the past two decades in terms of understanding the conditions and processes during the formation of the solar system. These strides have come in part from continued studies of solar system material, in part from advances in theoretical modeling of key processes thought to have played a central role in the formation of regions around mature and forming stars. The significance of the latter contribution is that it heralds the dawning of a new era in planetary science, in which the bridge between the study of our solar system as an isolated phenomenon is merged with studies of other examples of the phenomenon. It is not overstating the case to say that we will never fully understand the origin of our own planetary system without results from a successful search for and characterization of other planetary systems. Only then will we be able to determine which, if any, of the features of the solar system are proto-typical of planetary systems in general, and therefore, which properties must emerge as general results from a theoretical framework. We will begin to see the development of a new discipline, that of planetary system science, which will not only lead to an understanding of how our solar system was formed, but which will also provide a means to check our views of the process by which stars are born.

A star with a single planetary companion executes a reflex orbit that is a much smaller replica, in its projection on the sky, of the orbit of the planet itself. The dimensions of this stellar orbit are scaled down by the ratio of the planet to stellar mass. For a multiple planet system, the reflex motions of the star are independent and additive. The two measurable aspects of that stellar reflex orbit are the apparent displacement of the star, which can be sensed by precision astrometry, and the variation in its radial velocity, which can be detected by high-resolution doppler spectroscopy. These techniques are complementary, and both are maturing instrumentally to the point that their expected sensitivities in searches for other planetary systems are limited only by systematic effects associated with the physical properties of the stars themselves.



The appearance of Pluto and its satellite, Charon, as modeled by D. Tholen (Univ. of Hawaii) and M. Buie (Space Telescope Science Inst.), based on observations of mutual occultations. Ground-based occultation data have provided a unique opportunity to study these distant worlds. Reprinted by permission from D. Tholen (Univ. Hawaii) and M. Buie and K. Home (Space Telescope Science Inst.).

The doppler spectroscopy technique measures the radial (line-of-sight) component of the star's reflex motion to a precision of a few meters per second, using specialized spectroscopic instruments on large ground-based telescopes. This technique works most sensitively for low-mass stars, and it is especially sensitive to planets in smaller orbits. Doppler spectrographic surveys are under way at the University of Arizona, the University of Texas, and at the Canada-France-Hawaii telescope at Mauna Kea, where precisions of 10 m/s have been achieved over several years. The current state-of-the-art would permit the detection of Jupiter around the Sun at the 1-sigma level, and of a jovian planet in a smaller orbit around a star of 0.3 solar masses with much better confidence. The observers at Mauna Kea have accumulated a data base on about 20 nearby dwarf stars, and several of them show marginal evidence for planetary or stellar companions. The primary advantages of the doppler spectroscopic technique are that it can be implemented from the ground, and its power is explicitly independent of the distance to the star under study. In addition, doppler spectroscopy is in many ways complementary to astrometric searches, which are most sensitive to planets in larger orbits. The complementary nature and the cost-effectiveness of doppler spectroscopy programs commend them as an important part of the overall effort to search for planets.

An alternative approach to searching for other planetary systems is astrometry, in which the reflex orbit of the star is determined from precision measurements of its apparent position on the sky. Unlike doppler spectroscopy, the detection capability of astrometry is inversely proportional to distance. However, for nearby stars, astrometric precisions of 10 microarcsec should be achievable from Earth orbit, and this level of precision is sufficient to detect planets with masses comparable to that of Uranus, in orbits with radii comparable to that of Jupiter around any star within 30 LY of the sun. In space, either direct telescopes or interferometer systems can be designed to achieve the required level of precision.

### Comparative Planetology: Understanding Planetary Processes

Not all of planetary astronomy is focused on questions of the origin and evolution of the solar system. The major planets, and even many smaller objects, retain little memory of their beginnings. Instead, these objects have been subject to a long history of thermal and chemical modification, enhanced by random impacts and other external influences. To understand these planetary histories, and the conditions that determine planetary environments today, we must address the current state of the members of the solar system. Much of the current effort is also directed toward the dynamical processes that we see at work on other planets. As we develop a better knowledge of these processes, we can enhance our understanding of the forces that shape planetary evolution, and we may also develop a deeper understanding of our own planet Earth.

The following sections describe a number of opportunities to advance our understanding of planetary processes during the decade of the 1990's. Many of these focus on dynamic and time-variable phenomena. Most such studies require Earth-based astronomical studies, often spanning a considerable time base. Even when a spacecraft encounter has yielded a much more detailed study of a target at one particular epoch, these Earth-based studies must be made to relate the spacecraft data to events on the longer time scales characteristic of planetary seasonal changes or the 11-year solar cycle.

#### *Dynamics of Planetary Atmospheres*

The Voyager encounters with Jupiter, Saturn, Uranus, and Neptune have revealed great diversity in the dynamics and circulation patterns of the atmospheres of the giant planets. The winds vary greatly with latitude in a pattern that is unique to each planet. Saturn's winds, for example, are almost entirely eastward relative to the rotation of the magnetic field, while those of Neptune within 60 degrees of the equator flow westward. On Jupiter, the banded appearance of the atmosphere shows that planetary rotation plays the dominant role in global circulation, with rising air in the white zones and descending air in the dark belts, but this relationship is not valid for Saturn. Uranus shows essentially no atmospheric banded structure. Jupiter and Neptune, both of which have internal heat sources, each exhibit a gigantic storm system (the Great Red Spot and Great Dark Spot, respectively) at the same southern latitude and of comparable size relative to the planet's dimensions.

The depth of penetration of the zonal winds into the atmospheres of the giant planets and the energy source that drives those winds are unknown. Eddy activity on spatial scales that are below the resolution of Earth-based telescopes have only been glimpsed during the Voyager flybys and are poorly understood. Thus, our understanding of the coupling of the atmospheres to the motions of the interiors of the giant planets is very weak.

Many more observations with high spatial resolution and a time base comparable to that of the known seasonal and non-periodic changes are required to decipher the dynamics of the atmosphere of Jupiter and the other giant planets. At a resolution of 0.1 arcsec, Jupiter and Saturn can be studied on appropriate spatial scales. Unfortunately, there is little to be seen on Uranus, and Neptune is so distant that another order of magnitude in spatial resolution is probably required to monitor seasonal variations effectively. Much higher spatial resolution can be achieved near the 10  $\mu$ bar levels with stellar occultations, which can probe the structure of these atmospheres with a spatial resolution of a few kilometers.

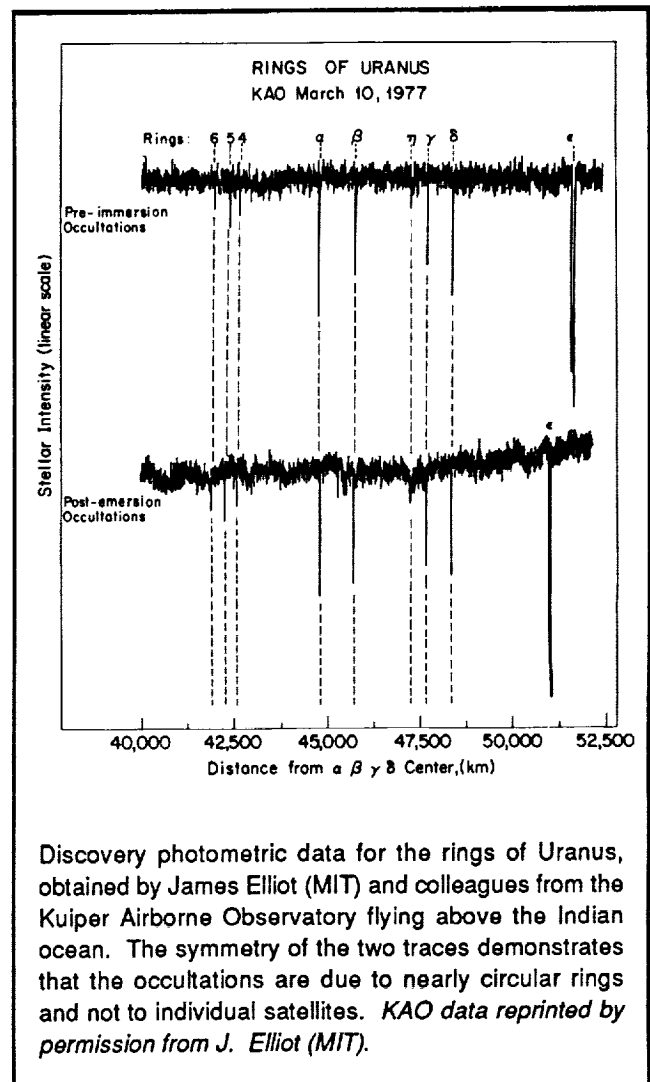
The wind patterns on Mars and Venus are not yet completely known nor understood. What is the circulation pattern in Venus' mesosphere? The underlying cloud layers show strong retrograde winds, while the thermosphere is expected to have a day-to-night wind pattern. Planetary-scale winds on Mars have never been observed, due to the absence of large stable cloud features in the atmosphere. The unknown winds on both planets can be observed by doppler spectroscopy utilizing rotational translations of the carbon monoxide line at millimeter wavelengths.

### Planetary Rings and Ring Dynamics

Observations of occultations of stars by solar objects will continue to be a major tool of planetary science. Apart from *in situ* measurements, there exists no other method for directly probing refractivity and optical depth. Occultation observations yield spatial resolutions on the order of a few kilometer (submilliarcseconds in the outer solar system), while constraining positional models to even higher precision, by one-to-two orders of magnitude. Such precision rivals or even exceeds many measurements from spacecraft, and is ultimately attributable to our precise knowledge of the position and rotation of the Earth. Occultation data can be continuously accumulated over a temporal baseline exceeding decades, which leads to continuous refinement of ring precession rates and related variables, which in turn provide precise geophysical measurements of quantities related to planetary interior structure.

The Neptune system presents a challenge to ground-based planetary astronomy over the next decade. The rings of Neptune are currently accessible to ground-based observation only via stellar occultation, and only the denser portions, or condensations, can be detected reliably. With the Voyager encounter data, we have a few sparse observations spread over an eight-year period. The orbital periods and radii of the condensations are so poorly known that predictions of their orbital phases over a decade-long baseline are subject to uncertainty of 10 degrees or more. No viable theoretical model for the condensations currently exists. Basic information about eccentricities, inclinations, precession rates, widths, and optical depths can be obtained from stellar occultations, but will require concerted worldwide campaigns and accurate predictions. Such a data set will provide fundamental constraints on ring theories, and may also yield accurate data on the interior structure of Neptune.

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Other ring systems amenable to study at high spatial resolution afforded by the stellar occultation techniques are those of Uranus and Saturn. A highly sophisticated model for the orbits of the nine "classical" uranian rings has already been achieved by combining occultation observations obtained over the past 13 years. Even more precision with which to test dynamical theories of this system is available through continuing observations, as the aspect of Uranus changes from a polar to an equatorial view.

Until recently, Saturn's rings had not been studied with Earth-based occultation observations because of the prohibitively bright background of the rings themselves. However, occultation by Saturn's rings have begun being observed from the ground with new infrared techniques. Also, observations will be possible with the Hubble Space Telescope (HST), SIRTf, and SOFIA when they become operational. These data will yield immediate improvement in the precision of determinations of Saturn's gravity zonal harmonics, some first order information on the shape of the inner edges of the A, B, and C rings, and completely new information on the more opaque portions of the B ring.

### *Composition and Structure of the Atmospheres of Giant Planets*

We are still learning much about the trace constituents of the atmospheres of the giant planets. Many important planetary molecular lines occur at wavelengths inaccessible from the ground, such as the 4 to 8  $\mu\text{m}$  region. Studies from the KAO have revealed the presence of water, phosphine, carbon monoxide, germane, ethane, and arsine on Jupiter. The higher sensitivity provided by SOFIA's large aperture and higher flight altitude will permit numerous investigations not attempted from the KAO, such as high resolution spectroscopy of Uranus.

At radio wavelengths (millimeter to centimeter) one typically probes into and below the cloud layers. The main opacity is provided by gaseous ammonia. Observations at different wavelengths probe different depths, and hence provide information on the altitude distribution of the ammonia gas. High resolution images give information on the spatial distribution of this gas. Since ammonia is the primary constituent of the cloud layers composed of ammonia ice and solid ammonium hydrosulfide, radio observations provide direct information on these two cloud layers. The information can be tied in with atmospheric composition and thus planetary formations, as well as with cloud physics and dynamics.

Currently, excellent images at centimeter wavelengths can be obtained with the VLA. It would be worthwhile, however, to put more effort over the next decade into software to enable deconvolution techniques such that the images can be corrected for rotational smearing (images have integration times of at least a few hours), which would allow detection of longitudinal features in addition to the latitudinal structure.

At millimeter wavelengths, radio interferometry can image the giant planets on arcsecond scales and yield information on the ammonia gas and on trace constituents such as carbon monoxide, hydrogen sulfide, hydrogen cyanide, and phosphine at relatively deep levels of the atmosphere. Such observations imply that these constituents, if present, are brought up from deep levels in the atmosphere, as opposed to being formed at high altitudes or introduced from outside the atmosphere.

### *Volcanoes of Io*

Jupiter's satellite Io is one of the most remarkable objects in the solar system. Its high level of volcanism, discovered by the Voyager spacecraft in 1979, is readily detectable from Earth, and observations made nearly a decade before the Voyager flyby can be interpreted in retrospect in terms of heat flow from volcanic hot spots. During the 15 years between Voyager and the arrival of the Galileo spacecraft at Jupiter, astronomical observations have permitted continuous monitoring of volcanic activity, and this ability to extend the time base of spacecraft data will continue into the future.

The volcanoes on Io channel the release of internal heat through a limited number of vents or hot spots that are observable from Earth in the thermal infrared region of the spectrum. The emission spectrum of the thermal regions is clearly apparent during eclipses, but even when not eclipsed the hot spots are detected, and with spatial resolutions of 0.1 to 0.3 arcsec individual volcanoes can be identified and studied in detail. Such studies have revealed the

locations, sizes, and temperatures of the main hot spots, as well as estimates of the total heat flow. One interesting discovery is that about 50 percent of the total heat flow from Io is focused in one volcanic region, called Loki, which has been active for at least two decades. However, there are indications of variations in the temperature, area, and perhaps exact location of Loki on time scales as short as a few weeks.

The infrared spectrum of Io shows many bands diagnostic of the ices that lie on its surface. Sulfur dioxide (including several isotopes), hydrogen sulfide, and water ice have been found, but several other absorption bands are as yet unidentified. The ices on Io's surface are presumably emplaced locally by the active volcanoes, but they are largely unstable because of the temperature and the radiation environment. Sublimation and recondensation redistribute the materials on the surface, perhaps in patterns corresponding to their volatility. The compositions of Io's ices are a reflection of the chemistry of the volcanoes, and they are spatially and temporally variable. Spectroscopy of Io with higher spectral resolution and expanded spatial and time resolution will be valuable in the continued study of the volcanism on this satellite.

Ground-based observations of Jupiter's magnetosphere are obtained regularly. In fact, the presence of Jupiter's magnetosphere, its strength, tilt angle, and offset from center were determined from ground-based observations well before the spacecraft encounters. Radiation at decimetric wavelengths is synchrotron radiation, emitted by high energy electrons near Jupiter's magnetic equatorial plane. The emission is a smooth function of central meridian longitude. Emission at decametric wavelengths is cyclotron radiation, emitted by electrons at or near their high latitude mirror-points. The emission appears in bursts, and is very irregular in character. The decametric emission is strongly modulated by Jupiter's central meridian longitude and the phase of Io in its orbit. More ground-based observations, with parallel modeling and theoretical investigations, are needed to add to the present knowledge of a number of unexplained effects such as a perplexing variety of types of bursts, polarization effects, and the presence of correlations with Io in some components and the lack of it in others. Long term monitoring is important to establish and investigate periodicities, to correlate the emissions with the solar wind or other solar phenomena, and to watch for effects that might reveal a non-periodic change in the jovian magnetic field structure or in its rotational period.

### *Mineralogy of the Martian Surface*

Many studies of the surface of Mars can be carried out from the Earth. The 2 to 6  $\mu\text{m}$  range is ideally suited for characterization of a variety of volatile-bearing minerals such as hydrates, hydroxides, water ice, carbon dioxide ice, carbonates, and sulfates. Some important features in this spectral range are accessible from the ground, while others require an airborne telescope. During the better oppositions the largest volcanoes are on the order of 1 arcsec in size, and polar caps are somewhat larger. Spectroscopy with comparable spatial resolution should isolate characteristic mineralogy, and permit geologic interpretation of the regional internal and surface processes which have been active throughout the planet's history.

Examination of photographs of the surface of Mars leads to the inescapable conclusion that there once must have been large quantities of fluid on the surface. Yet no obvious fluid sources are apparent today. Water vapor has been detected in the atmosphere of Mars and has been shown to be variable. The source of the water vapor is thought to be a permafrost trapped under the polar carbon dioxide ice caps. In support of the current Presidential and NASA initiative toward Mars, it is critical to continue to monitor the quantity of water vapor on Mars in order to quantify the atmospheric water cycle and to understand the seasonal cycles of the atmosphere.

### *High-Precision Dynamical Studies*

We are used to thinking of many astrophysical measurements as being not very precise, i.e. as carrying no more than two or so significant figures. These are the type of measurements which are of most interest when we are in the discovery mode, when the mere existence of a phenomenon is in question. Much, but not all, of the work of ground-based planetary astronomy has been in this mode. But detailed comparison of theory and observation to several significant figures has also led to an elegant and profound syntheses. The planet Neptune was discovered in this fashion, and even in the twentieth century the careful analysis of orbits and spins has led to the discovery of subtle resonances. Most recently, careful and precise measurements of the mutual eclipses and occultations of the Pluto-Charon system has produced determinations of the sizes and orbital parameters to many significant figures.

Some examples of the precise measurements which are of interest follow: 1) The orbits of the Galilean satellites of Jupiter are evolving under the influence of tidal dissipation and exchange of angular momentum with Jupiter. Determination of the evolution of these orbits is possible, in principle, with high-precision observations of

orbital phases over long temporal baselines. Some observations of this type may not be fully exploitable for many generations, but should be made now; 2) the shape parameters (both gravitational and geometrical) of planets are influenced by their spin states and by internal dynamics. It is feasible to measure these parameters to the level of a few kilometers in some cases, and over a period of years to build up a data base for detailed study of interior structure, as has been done for the Earth; and, 3) the jovian magnetic field, unlike the fields of the other giant planets, can be readily observed from the Earth, and its rotation period can be determined to a fraction of a second. According to dynamo theory, the geometry of the jovian field should be evolving, and one would expect to obtain information about such evolution if the current level of precision of observations were maintained for about a century.

## CRITICAL TECHNOLOGY DEVELOPMENTS

The continuing success of planetary astronomy, even in the era of space missions, can to a large degree be attributed to technological advances in instruments, telescopes, and data reduction methods. New technology facilitates observations that have been previously impossible from Earth, and these open up new areas of scientific investigation. A recent example is the imaging of the Io volcanoes from the IRTF at 0.3 arcsec resolution. With this capability we can now watch new volcanoes emerging and old ones becoming dormant.

Obtaining these volcano images became possible just recently with the incorporation of an infrared array into a new instrument (the Proto Cam) at the IRTF and a better understanding of the seeing (degree of atmospheric interference) at Mauna Kea, which shows that images as small as 0.2 arcsec can be obtained in the near infrared region of the spectrum. A further bonus of this wavelength region is that the jovian planets have deep methane absorption bands, so that most, if not all, of the small satellites discovered by Voyager can now be studied from Earth.

Future technical advances will have similar impacts, since we are now in the midst of rapidly improving capabilities in several critical areas, including: 1) improvements to telescopes and the image quality that can be obtained from them; 2) increases in array detector size to cover an expanded wavelength region with lower background noise; 3) improvements to computer technology that are providing dramatic increases in speed, high capacity data storage, and worldwide network capabilities that will be needed to cope with the array data; and, 4) development of new, high-level software languages, some of which work with symbolic, as well as numeric input (such as IRAF, IDL, and Mathematica), thus dramatically reducing the time needed to develop and implement new methods for modeling and data analysis.

In the past decade planetary astronomy experienced a revolution brought on by the common use of the charge coupled device (CCD) as a detector. This device has had a particularly large impact on comet observations, which make full use of all four advantages that the CCD has over a photographic plate: 1) higher quantum efficiency; 2) larger dynamic range; 3) lower background noise; and, 4) output data already in digital form. At present, however, the greater number of pixels on a photographic plate still makes it the preferred detector for some survey programs, such as searches for new comets and Earth-approaching asteroids. This advantage will disappear as 2048 x 2048 arrays become available. Although infrared arrays are smaller (256 x 256 at present), they may have even greater impact on planetary astronomy than the optical CCD because of lower background fluxes from the jovian planets and the superior image quality in this spectral region.

As a result of these technological advances, we can expect not only higher quality data in the 1990's from Earth-based telescopes but the development of more efficient ways for planetary astronomers to work. The interconnection of the community and observatories through a common computer network will make it easier to share supported software. Another advantage of the ubiquitous computer network will be the facilitation of remote observing and data access. After an observing program has been set up and the observing techniques established, the program can be carried out by a local observer or through control of the telescope and instrument from a remote location. This will reduce travel time and costs and allow sharing nights between observing programs. The flexibility gained by remote observing could also be used to increase the effectiveness of certain observing programs.

Looking to the late 1990's and beyond, fundamental advances in the study of asteroids and other small solar system objects will be possible with the development of ground-based interferometers. Systems under development by several groups are expected to yield images of stellar sources with milliarcsecond resolution within a decade. Applications to solar system objects, with their lower surface brightness and irregular contours, may be more difficult, and they are expected to require both advanced adaptive optics and interferometer systems with extensive coverage of the U-V plane. However, eventually we hope to obtain asteroid images from the ground with resolution of a few kilometers throughout the main belt.

The extension of interferometric imaging to long baselines in space offers even more dramatic capability. A 10-kilometer baseline interferometer on the Moon could achieve resolution of a few tens of meters for the main belt asteroids. Such an instrument would also be expected to have astrometric accuracy of about 10 nanoarcseconds, opening a much larger volume of space to astrometric searches for extra-solar planets.

## PROPOSED PROJECTS AND FACILITIES

The following are brief descriptions of the major new projects proposed for the 1990's that hold the greatest promise for new discoveries and deeper insight in planetary astronomy. They appear here prioritized according to their cost within the "space-based" and "ground-based" categories.

### SIRTF: The Space Infrared Telescope Facility

SIRTF is a 1-meter class cryogenic telescope, designed to operate for five years in high Earth orbit (altitude approximately 100,000 km). SIRTF is the infrared component of NASA's family of Great Observatories, and it is currently planned for launch in the late 1990's. It will be operated as a facility for the entire scientific community, with over 80 percent of the observing time available to general observers. SIRTF's three instruments will provide images and spectra from 2  $\mu\text{m}$  to beyond 700  $\mu\text{m}$ , using an optical system which will provide diffraction-limited images at wavelengths longer than 3  $\mu\text{m}$  over a 7-arcmin field of view. Using current infrared detector arrays, SIRTF will be natural background limited, and on a per-pixel or per-resolution element basis, it will be 1,000 to 10,000 times as sensitive as IRAS. SIRTF will be the first mission to combine the intrinsic sensitivity of a cryogenically-cooled telescope with the tremendous imaging and spectroscopic power of large-format detector arrays.

SIRTF will expand upon the important discoveries by IRAS of the disks and shells of particulate matter orbiting nearby stars. SIRTF will make detailed imaging studies of the most prominent disks to determine their shape and orientation, and to search for the dust-depleted inner regions predicted by models which may suggest the presence of planets close to the stars. Low resolution spectroscopy will be diagnostic of the composition of the dust in these systems, while high resolution spectra will trace gaseous constituents. SIRTF can detect less prominent dust systems around literally thousands of stars and determine how the prevalence and properties of such disks depend on the mass, luminosity, age, and other characteristics of the stars. These dust disks are spatially extended and thus demand the low background of a cryogenic telescope. SIRTF is the ideal platform for such studies, which can revolutionize cosmogony by extending the study of planetary system formation beyond the boundaries of our solar system.

The reconnaissance of the outer solar system accomplished by the Pioneer and Voyager spacecraft and the survey work of IRAS have revealed new aspects of the Sun's family that require further detailed study. Just as SIRTF can study material in the outer regions of other solar systems, it will extend the studies of our own solar system to the most distant planets and beyond. SIRTF will obtain spectra of comets, asteroids, and planetary satellites in the infrared region, where diagnostic molecular bands reveal the chemistry of these varied objects. The ices that condensed in the collapsing solar nebula further than 5 AU from the Sun and that are now locked in the comets and satellites carry the chemical history of the nebula in the zones where the outer planets formed. The chemistry of carbon, oxygen, and nitrogen in the solar nebula and in the protoplanetary clouds can be read in the spectral signatures of the comets and the relatively undisturbed planetary satellites. Organic solids and other forms of carbon, preserved from the interstellar medium and incorporated into the comets and asteroids, can be explored through their infrared spectral signatures in objects too faint and cold to be observed from ground-based telescopes. Infrared auroras on the giant planets will be observed spectroscopically, while spectra of the volcanically active Io will reveal the ever-changing surface and atmosphere. Far-infrared spectra of Pluto, Chiron, and Triton will, for the first time, give definitive information on the atmospheres and surface ices of these small and remote bodies. Dust from pulverized asteroids found by IRAS will be explored in high-resolution thermal infrared images to determine the sources and ages of specific asteroid collisions. SIRTF can also search for the hypothesized Kuiper belt, thought to represent a reservoir of comets beyond the orbit of Pluto. If this belt is as rich as is required by some recent dynamical estimates, one or two Kuiper belt comets should appear in a single SIRTF image taken in the zodiacal plane at 100  $\mu\text{m}$ ; these faint objects can readily be identified by their gradual motion relative to the galactic background.

SIRTF is the fourth and final of NASA's orbital Great Observatories, and as such it is the highest priority major new project of the Astrophysics Division. Assigned to JPL for implementation, it will receive a Phase B study in 1992. In the strategic plan of the NASA Office of Space Science and Applications, SIRTF is scheduled as a proposed FY93 new start, with launch anticipated for about 1998.

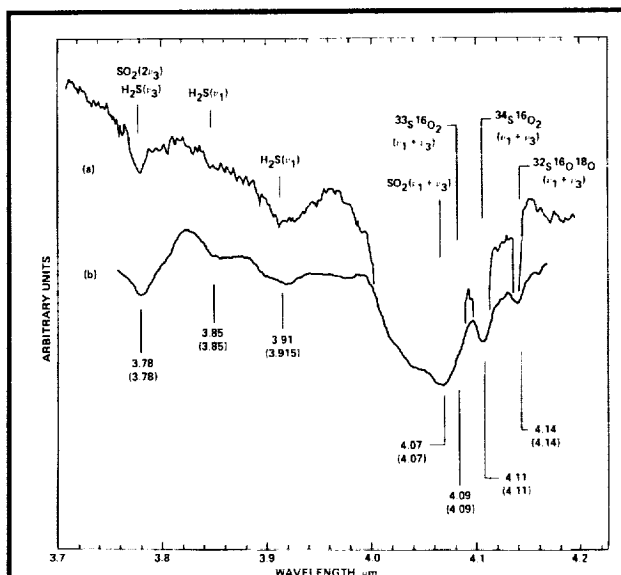
### SOFIA: The Stratospheric Observatory for Infrared Astronomy

SOFIA will be an airborne observatory designed to address fundamental questions in galactic and extragalactic astronomy and in the origin and evolution of the solar system. Operating at altitudes from 12.5 to 14 km, SOFIA will provide routine access to wavelengths between 0.3  $\mu\text{m}$  and 1.6 mm. Its 2.5-meter-diameter telescope will produce images ranging from roughly 4 arcsec at visible wavelengths down to about 1.5 arcsec in the near infrared region of the spectrum, and following the diffraction limit for wavelengths beyond about 10  $\mu\text{m}$ . The planned schedule of 120 8-hour flights per year would support approximately 15 focal plane instruments and 40 P.I. teams annually. Many of these teams would involve one or more graduate students. The instruments would include photometers, polarimeters, and spectrometers developed and maintained largely by the interested P.I. teams. SOFIA's 20-year lifetime will provide a foundation of research, instrument development, and training of young scientists, bridging the gap between IRAS and SIRTF.

SOFIA will permit exciting new studies of the mineralogy of the martian surface. The 2 to 6  $\mu\text{m}$  range is ideally suited for characterization of a variety of volatile-bearing minerals such as hydrates, hydroxides, water ice, carbon dioxide ice, carbonates, and sulfates. A number of important features in this spectral range are accessible from an airborne telescope. Spectroscopy from SOFIA should isolate characteristic mineralogy and permit geologic interpretation of the regional internal and surface processes which have been active throughout the planet's history.

Occultations of stars provide a powerful tool for the study of planetary atmospheres and rings. The altitudes of a planetary atmosphere probed by an Earth-based stellar occultation lie in the gap between spacecraft radio occultations and ultraviolet stellar and solar occultations. A series of stellar occultations by a planetary ring system can provide exceedingly precise orbital data, leading to an understanding of the age and evolution of the rings and to the internal structure of the planet through the harmonics of its gravitational field. SOFIA will readily accommodate the specialized instrumentation required for occultations, typically high time resolution, multispectral imaging systems. For example, the quality of an occultation observation is enhanced by working in wavelength bands where the planet is relatively dark. In the case of Saturn for example, 6.2  $\mu\text{m}$ , a wavelength accessible from SOFIA but not from the ground, is an intensity minimum for both the disk and the rings. SOFIA will be a primary facility for observation of stellar occultations by Pluto, Triton, and Titan by virtue of its large aperture and mobility. Events involving these interesting objects will commonly involve faint stars, and will have uncertain predictions until a few days before the event occurs. Thus its sensitivity, mobility, scheduling flexibility, and insensitivity to weather assure SOFIA a unique role in the observation of occultations.

Spectroscopic studies of comets will make use of the spectral access available to a stratospheric telescope. The discovery of water vapor in Comet Halley from the KAO clearly demonstrated the value of airborne observations of comets. Ground-based measurements of Halley revealed organic material (the C-H stretch feature), but important



Infrared spectrum of Jupiter's satellite Io (solid curve) compared with laboratory spectra of possible analogue materials. Infrared spectroscopy is one of the most powerful tools for determining the compositions of both planetary atmospheres and solid surfaces. *Courtesy of F. Salama (NASA Ames Research Center).*

C-O, C-C, and C-N stretch bands of these species lie between 5 and 8  $\mu\text{m}$ . Moreover, important cometary parent molecules have strong rotational transitions at submillimeter wavelengths. Radiation in these infrared and submillimeter bands does not reach the ground but is readily accessible from 12.5 km. Gaseous constituents require high resolution (roughly 1 km/sec) to discriminate between telluric and cometary features, to separate vibration-rotation lines in a band, and to permit kinematic analyses of cometary line profiles. SOFIA will be able to study a number of short period comets, observing their solid-state spectral features (such as olivine and water ice) as well as their gaseous features.

SOFIA will retain the major features of the Kuiper Airborne Observatory that have made the airborne astronomy program so successful, including flexibility of operations and broad access to investigators and their students. Particularly important are the opportunities offered to young scientists, who can accomplish complete astronomical investigations - from instrument concept and construction, through publication of results - within the time available to a graduate student or post-doctoral researcher. SOFIA will help bridge the gap between ground-based and space-based astronomy in the educational sense, as well as in its access to the electromagnetic spectrum. Extrapolating from experience with the KAO, one can project that SOFIA, over its 20 year lifetime, will generate nearly 100 Ph.D.s and involve participation by individuals from more than 150 institutions, about 70 percent of which will be universities.

SOFIA will be a joint project under U.S. leadership with the Federal Republic of Germany supplying a major part of the telescope system, supporting the operations at roughly the 20 percent level, and participating in the flight program at a similar level. NASA and the German Science Ministry completed Phase B studies of the project in 1989 and are currently continuing technology studies at a lower level. If approved for development in NASA's FY92 budget, SOFIA will be flying in the fall of 1996.

### Search for Other Planetary Systems from Earth Orbit

The search for, and study of, other planetary systems can be a centerpiece of astronomy for the 1990's. Current ground-based studies using doppler spectroscopy and astrometry have the capability to detect Jupiter-mass planets orbiting the nearest stars. An improved astrometric telescope at an excellent site (discussed below, on page 17) could expand the search domain and extend to planets with the mass of Saturn. In addition, NASA's Search for Extraterrestrial Intelligence (SETI) project will begin operation in 1992, providing a radically different possibility for the discovery of other planets. If planetary systems are as prevalent as many astronomers believe, it seems likely that one or more of these surveys will achieve a positive result during the first half of the decade of the 1990's.

The discovery of one or more planets of jovian mass will be an important milestone, but it does not end the search for other planetary systems. The goal of a scientific survey must include the characterization of other planetary systems. To achieve this goal, we must use a search technique that is sensitive to smaller planets, at least down to the 10-Earth-mass level represented by Uranus, Neptune, and the refractory cores of Jupiter and Saturn. Further, we must anticipate that multiple-planet systems will be discovered, and that we will wish to determine the orbits and masses of these objects from their superimposed gravitational effects. The only technique capable of achieving the required accuracy is astrometry carried out at the 10-microarcsecond level for a period of a decade or more. Further, astrometry at the 10-microarcsecond level can provide definitive negative results in the search for other planetary systems; that is, failure to find any planets with such a search will challenge current ideas of the star and planet formation processes, and would therefore lead to a profound re-evaluation of current astrophysical thinking in these areas.

To achieve 10-microarcsecond precision, we must place an astrometric telescope beyond the Earth's atmosphere. In the long run, such surveys may best be carried out by interferometers on the surface of the Moon, and such systems should be carefully studied during the 1990's. However, it is also possible to pursue these goals with a free-flying astrometric observatory that could be launched and begin operation late in this decade. One example of the latter is the Astrometric Telescope Facility (ATF), a system capable, in principle, of relative astrometric measurements accurate to the several-microarcsecond level.

In addition to astrometry, which is an indirect method of detecting other planetary systems, there will be a need for systems capable of directly detecting other systems, or at least providing very high spatial and spectral resolution of disks which are likely precursors to planetary systems. In the region immediately adjacent to any bright point source lies a previously unexplored part of the universe. It is in this region that knowledge of the existence, origin, and formation of planetary systems lies hidden, masked by the scattered and diffracted light halo of the central source which blinds the optical system. The Astrometric Imaging Telescope (AIT) is a 1.5- to 2-meter-aperture orbital

telescope which has unique capabilities to overcome this blinding light source and which combines direct imaging and astrometry to discover and characterize planetary and protoplanetary systems.

The astrometric function is implemented by a relatively wide field (20 arcmin) astrometric instrument, the Multichannel Astrometric Photometer (MAP). The imaging function combines a newly developed, highly efficient coronagraph (working against diffracted light) with a super-smooth optical system (working against scattered light) to form the Circumstellar Imaging Instrument (CII).

The imaging capability of the AIT is a powerful adjunct to all indirect methods. By design, it is extremely sensitive to circumstellar material such as zodiacal dust distributions or protoplanetary disks. Moreover, in the case of multiple planets, the image formation recorded from each planet is spatially distinct and detectability is not a function of the number of planets. In other words, all planets in a given system that are above the detectability threshold for that system are detected independently of one another within the same images. Even when no detections occur, upper limits can be placed on the absence of planets larger than a given diameter at a given orbital radius. This kind of information can be expected to help resolve any ambiguous indirect signals.

The high efficiency coronagraph and the super-smooth optical system of the AIT combine to produce a reduction of the light halo around a bright star by three orders of magnitude. Taking into account relative aperture sizes and optical figures, this amounts to a hundred-fold improvement in background level over comparable levels in the Hubble Space Telescope. This dramatic reduction in background is necessary to image extra-solar jovian planets, but it also implies that we will be able to do much more than learn that there is some nebulous region surrounding a given star; we will be able to image fine detail in that region and directly observe subtle features which would otherwise totally exhaust the dynamic range capabilities of typical imaging systems.

The AIT has been recommended to NASA's Solar System Exploration Division and is currently under study (Phase A) at JPL. If supported either through science funding for Space Station Freedom or as a free-flying spacecraft, it could begin operations before the end of the 1990's.

### The Orbiting Planetary Telescope (OPT/PTEL)

The Orbiting Planetary Telescope/Planetenteleskop (OPT/PTEL) is a free flying 1-meter diffraction-limited telescope in high Earth orbit (geosynchronous). It is designed for an anticipated lifetime of 5 years and optimized for spectroscopic and high-resolution imaging of solar system objects. OPT/PTEL offers the following capabilities:

- Wide spectral coverage (115 to 5000 nm) free of atmospheric absorption.
- Fully multiplexed spectroscopy and imaging.
- Multiplexed ultraviolet-visible-infrared spectroscopic channels.
- Wide field of view (10 arcmin).
- On-target guidance and tracking to  $\pm 0.02$  arcsec.
- Operation at small solar elongation angles.
- 17 hour/day operation above 40,000 km.

The long lifetime of OPT/PTEL will allow investigation of time-variable solar system phenomena and their response to changing input conditions (e.g. variable Extreme Ultraviolet (EUV) flux, changing heliocentric distance, climate, and/or episodic volcanism.) Applied to studies of Mars it should provide insight into the origin and development of global dust storms and could play an enabling role in the human exploration of Mars. The ability of OPT/PTEL to provide near-simultaneous measurements in widely separated spectral regions should allow it to provide data that will clarify the complex physical inter-relationships that occur in phenomena like the Jupiter-magnetosphere-torus-Io system, the Venus cloud-deck, and in active cometary atmospheres. It could be used to extend and clarify measurements made by orbiting or flyby planetary spacecraft by providing the measurements that define the large-scale context of *in situ* studies. For example, ultraviolet spectroscopy of comet Kopff will directly support the *in situ* spacecraft exploration of this comet in the first decade of the next century. It could also be employed to study the long-term evolution of phenomena in planetary atmospheres (e.g. outer planet atmospheric circulations), and on planetary surfaces (e.g. martian polar caps). Finally it will allow further geochemical mapping of the lunar and martian surfaces as well as a survey of the unexplored hemisphere of Mercury.

During its nominal lifetime the telescope would provide some 12,000 hours of prime observing time (equivalent, after taking into account typical weather factors and atmospheric seeing, to 17 years worth of prime-time (dark) observations on a ground-based telescope.) In its operation phase the project is conceived to operate in a mode similar to the highly successful IUE mission, but with the addition of a fully distributed data system that will allow

fine targeting and data acquisition from the observers' home institution. It will provide rapid access to space for planetary scientists and therefore more frequent opportunities for novel solar system investigations in spectral regions unavailable from the ground.

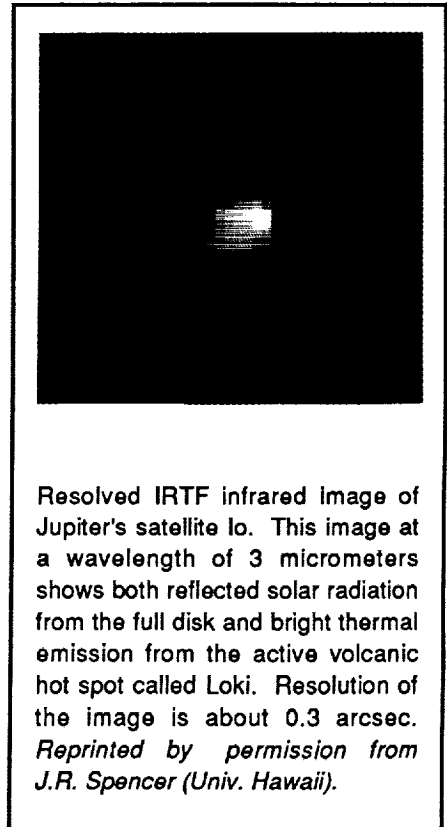
OPT/PTEL is conceived as an international project between the Federal Republic of Germany, the United States, and, possibly, the European Space Agency. The United States' contribution would be the provision of the ultraviolet-visible-infrared spectrographic package, associated foreoptics, and detector cooling systems. The mission therefore provides opportunities to hardware development groups at U.S. universities and private institutions while maintaining a substantial role for a NASA center. NASA's Solar System Exploration Division has recently formed a Science Working Group to work with European partners in completing a Phase A study for the OPT/PTEL, which could be proposed for new start funding in 1994 and launched in 1998.

### Infrared-Optimized 8-meter-Class Telescope

Astronomy in the U.S. is presently in a vigorous period of telescope construction; there are at least 11 projects under way or being planned for new ground-based telescopes in the 3- to 10-meter class. One of the current premier infrared telescopes in the world is the 3-meter IRTF on Mauna Kea, constructed and operated by the Solar System Exploration Division at NASA. Half of the time on the IRTF is devoted to solar system studies, and this instrument has supported a significant fraction of all ground-based planetary astronomy during the 1980's. Now, however, it is opportune to take advantage of new technologies to construct a much larger infrared-optimized telescope in the 8-meter class. Such a facility would be an enormous improvement over any currently existing telescope, and it would provide the focus for much ground-based research in planetary astronomy and solar system formation.

Although several other 8-meter optical/infrared telescopes are planned or under construction, none of these is optimized for the infrared region of the spectrum. On an infrared-optimized telescope the mirror coating would be of the lowest emissivity possible (either gold or silver); however, such coatings are detrimental to the ultraviolet/optical performance of the telescope and would not be used on a general purpose telescope. Second, the infrared secondary mirror would be very small, producing a central obscuration of about 0.25 percent. Third, the secondary structure of the telescope would be of low emissivity. Fourth, the mirrors would be protected from dust, cleaned, and re-coated frequently to maintain the low emissivity of the mirrors. Finally, the telescope must incorporate active optics to ensure diffraction-limited resolution at near-infrared wavelengths. Coupled with state-of-the-art infrared instrumentation, this telescope would be the premier infrared telescope in the world. Significant studies that could be undertaken with this telescope include:

- Studies of the disks of young stars. With the 30 to 70 milliarcsec spatial resolution that is possible with diffraction-limited imaging at 1 to 2.2  $\mu\text{m}$ , it is possible to obtain imaging at 5 to 10 AU on the nearest molecular clouds.
- Imaging of small bodies near bright planets. With an 8-meter telescope and advanced infrared imaging techniques, virtually all of the satellites discovered by Voyager could be routinely observed from Earth.
- Sensitivity to detection of faint planetary objects. A very deep survey of the composition, size, rotational periods, and density distribution of primitive objects could be undertaken with an 8-meter telescope.
- High spectral resolution observations. An 8-meter telescope provides sufficient aperture to carry out high spectral-resolution observations efficiently.



Resolved IRTF infrared image of Jupiter's satellite Io. This image at a wavelength of 3 micrometers shows both reflected solar radiation from the full disk and bright thermal emission from the active volcanic hot spot called Loki. Resolution of the image is about 0.3 arcsec. Reprinted by permission from J.R. Spencer (Univ. Hawaii).



- Stellar occultation observations. With an 8-meter infrared telescope, the frequency of potentially observable occultation events becomes great enough that events can be chosen on the basis of systematic physical studies of atmospheres and ring systems.
- Detecting hot young super-planets, larger than Jupiter, around stars out to a distance of several hundred light years.

This telescope will also provide important support to NASA's CRAF mission, which will reach Comet Kopff in July 2000. It should be able to detect thermal radiation from the comet nucleus (nominally a few kilometer in diameter), near aphelion, thereby permitting a determination of its diameter in time to aid planning of spacecraft observing sequences. Additional observations of other Jupiter-family comets will help in extending results from this mission to a broader population of perhaps similar objects.

Studies of infrared-optimized telescopes are currently underway. One option is to optimize for infrared work one or more of the two 8-meter telescopes planned to be constructed by the National Optical Astronomy Observatories with support from the NSF. An alternative is to consider an 8-meter-class telescope as a possible replacement for the NASA-supported 3-meter infrared telescope (IRTF) built on Mauna Kea in the 1970's.

### **Arecibo Radar Facility Upgrade**

Radar observations have yielded a wealth of new information about the physical properties of satellites, comets, asteroids, and the surfaces of the terrestrial planets. The most powerful radar facility in the world is the Arecibo radio-radar telescope in Puerto Rico, which is part of the National Astronomy and Ionosphere Center, operated by Cornell University under contract with the NSF. The instrument consists of a 305-meter-diameter fixed reflector, the surface of which is a section of a 265-meter-radius sphere. Movable line feeds suspended from a triangular platform some 130 m above the reflector correct for spherical aberration and can be aimed toward various positions on the reflector, enabling the telescope to point up to 20 degrees from the zenith. NASA support in the mid-1970's made possible the installation of the 2380-megahertz (13-centimeter) radar system, and annual support from NASA since then has proven essential to the continued operation of this unique facility. As a national center, Arecibo is accessible to the entire scientific community.

A recent proposal to NASA and the NSF for upgrading the Arecibo telescope calls for: 1) constructing a ground screen around the periphery of the dish; 2) replacing the higher frequency line feeds with a much more efficient Gregorian sub-reflector configuration; 3) doubling the output power of the 13-centimeter transmitter; and, 4) installing a fine-guidance pointing system. These upgrades will increase the instrument's average radar sensitivity by a factor of 20, more than doubling its range and reducing by nearly an order of magnitude the diameter of the smallest object detectable at any given distance. The quality, in terms of signal-to-noise ratio and/or spatial resolution, of all measurements performed routinely today would jump by more than an order of magnitude.

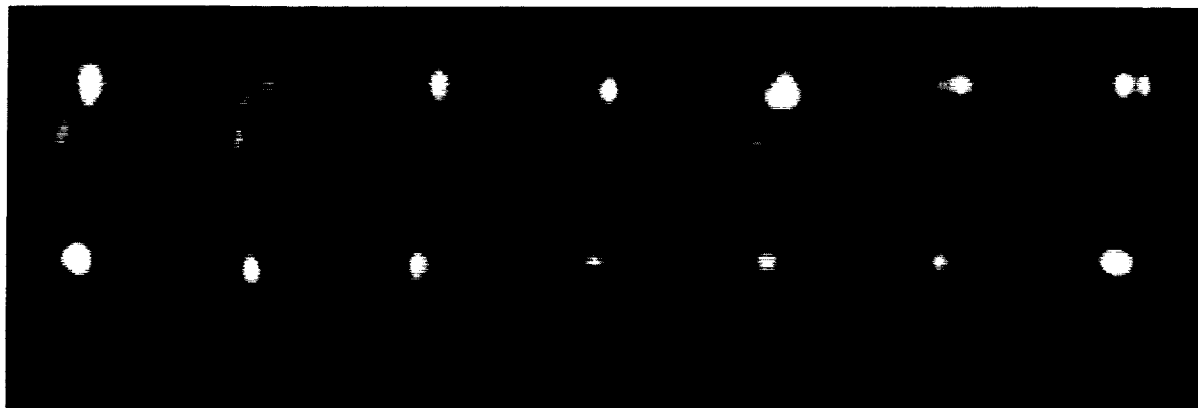
The impact of an upgraded Arecibo on planetary science will be fundamental and far-reaching, especially for studies of small bodies and planetary satellites. During its first decade of operation, the instrument will provide high resolution images of about 30 near-Earth asteroids and 100 main belt asteroids. Currently, Arecibo can barely skim the inner edge of the main asteroid belt, but an upgraded instrument will have access to asteroids throughout the belt. Short-period comets, which generally lie at the edge of the current detectability window, will become easy targets, letting us determine their nuclear characteristics and check for the presence of large-particle clouds. The asteroid flyby target of NASA's CRAF mission (Hamburga) will be accessible during its November 1993 apparition, when radar data can improve the orbit determination. A better orbit for Hamburga will be essential for ensuring maximum return from the 1997 spacecraft flyby, which otherwise will risk losing many of its close-up photographs due to pointing uncertainties. Similarly, asteroid Maja, targeted for a Cassini flyby in 1997, will be accessible to the upgraded Arecibo facility in February 1994.

Radar investigations of natural satellites will reap enormous benefits, especially for Io and Titan, whose near-surface physical properties and centimeter to kilometer structural properties will be readily discernible. The regoliths of the icy Galilean satellites could be probed to depths of 100 m or more and studied on a global scale, and the subsurfaces of Phobos and Deimos could be compared in detail. Iapetus will be detectable, and radar measurements could elucidate near-surface morphology and the disparate hemispheres of this unusual object.

Most elements of the Arecibo upgrade have been approved by NASA and the NSF. Barring unforeseen difficulties, the new capability should be fully in place by 1994.

### Astrometric Telescope for Planet Detection

Doppler spectroscopy, which can be used to measure extremely small motions of stars in response to unseen orbiting companions, is a powerful technique for the detection of other planetary systems. The level of precision already achieved (10 m/s) opens an important segment of the phase space that might be occupied by other planetary systems; namely, those consisting of compact planetary systems accompanying low-mass stars. Present doppler spectroscopic observing programs, if extended to a sample of 100 or more G and K dwarfs and continued for a decade, should provide a definitive determination of whether such stars have compact planetary systems that include objects of jovian mass. Such a study constitutes an essential part of the systematic search for other planetary systems.



Arecibo radar images of the Earth-approaching asteroid 1989PB. The object, which is only about 400 m long, is resolved to show what appears to be a contact binary. The upgraded Arecibo radar will be able to reach hundreds of asteroids with this resolution. *Arecibo data, courtesy of S.J. Ostro (JPL).*

Astrometric searches for other planetary systems complement those carried out by doppler spectroscopy, in that they are more sensitive to extended rather than compact planetary systems. Current ground-based astrometry, at a precision of 2 to 4 milliarcsec, is capable of detecting a jovian-mass planet only for the nearest few dozen stars, and only if the stellar mass is less than about 0.3 solar masses. Thus, our own planetary system remains below the current detection threshold. However, the gains in astrometric precision that can be achieved with a dedicated modern astrometric telescope at a site with excellent seeing should permit studies with precision as good as 500 microarcsec, thereby bringing a wider variety of potential planetary systems within range.

Ground-based astrometry, with a dedicated telescope at an excellent site, will effectively complement the doppler spectroscopic method and will bring within our reach another significant segment of planetary system phase space. Such a telescope will be capable of detecting the reflex astrometric motion of G and K dwarf stars produced by planets of jovian or saturnian masses in orbits with radii greater than about 4 AU. The periods for such orbital motion are typically in the range of 5 to 10 years, so an extended survey is required. At least 100 stars are within range of such an astrometric telescope with modest aperture (1 to 2 m). An additional task for an astrometric telescope that would be important for planetary astronomy is its use for the accurate prediction of stellar occultations by bodies subtending small angular diameters, such as Triton, Charon, and Pluto.

The construction of a modern ground-based astrometric telescope is a next step in the search for other planetary systems. Such an instrument has been proposed to the NSF for construction on Mauna Kea. It should provide important fundamental data (e.g. proper motion, parallax) for stars and it will serve as a test bed for future astrometric instruments in space, as well as offering a good prospect of discovering one or more other planetary systems. Beginning the search now from the ground is both timely and prudent. The results promise to be exciting, and the experience will be invaluable as a precursor to the more advanced orbital facilities to follow, such as the system described above, on page 14.

## RECOMMENDATIONS

### Projects and Facilities: Prioritized Panel Recommendations

The Planetary Astronomy Panel finds that all of the projects and facilities discussed above are of the highest scientific merit. Each of them can be implemented during the 1990's (although not in all cases be fully operational before the end of the decade), and each will be of immense benefit to astronomers in addressing the exciting scientific challenges outlined in this report. We have categorized each of these in terms of cost and present the following recommendations, prioritized within each cost category. No effort has been made to prioritize one category against another, however.

Major Space-based:	1. Space Infrared Telescope Facility (SIRTF)
Moderate Space-based:	1. Stratospheric Observatory for Infrared Astronomy (SOFIA) 2. Search for Other Planetary Systems from Earth Orbit
Small Space-based:	1. Orbiting Planetary Telescope/Planetenteleskop (OPT/PTEL)
Major Ground-based:	1. Infrared-Optimized 8-meter-Class Telescope
Moderate Ground-based:	1. none
Small Ground-based:	1. Arecibo Radar Upgrade 2. Astrometric Facility for Planet Detection

### Additional Recommendations

**Research Support.** Good science is a highly individualistic process that requires the participation of many researchers. Programs of individual research grants should be strengthened, and for these small grants the administrative system should impose a minimum of management or control beyond what is necessary to assure reasonable accountability. It is essential that inflationary erosion of the NASA and NSF grants programs be reversed and that funding levels permit new investigators to join the ranks of planetary astronomers.

**Instrumentation.** Progress in development of astronomical detectors and instrumentation, exemplified during the past decade by the CCD and 2-dimensional infrared arrays, has greatly increased the power of existing telescopes and has opened the way for spectacular advances during the 1990's. Many of the instruments built for the general support of astronomical research are also appropriate to planetary research. But planetary astronomy also has special requirements, for example in the need to study faint objects close to bright ones. It is important that funding be available to construct instruments optimized for planetary observations, if the promise of new observing facilities is to be realized.

**Access to Telescopes.** Planetary research often places unusual demands upon telescopes and scheduling committees. Many planetary events of high interest, such as occultations or the observations of newly discovered comets and asteroids, either make very specific requirement on time or are not predictable long in advance, or both. Some observations require the coordinated efforts of many telescopes working in concert. Observatory Directors and telescope scheduling committees are encouraged to consider these special needs and to retain sufficient flexibility to schedule planetary observations in spite of their sometimes complex requirements.

**Telescope Support.** Planetary astronomy has profited greatly from the construction and operation of ground-based facilities for planetary research, such as the IRTF in Hawaii or the planetary radar system at Arecibo. We commend NASA for its special efforts to recognize the unique needs of planetary astronomy, and we encourage the agency to continue to play a leading roll in the development of future facilities for planetary astronomy.

**Surveys.** Many important problems in planetary astronomy require a search for new objects (e.g. comets and Earth-approaching asteroids) or the systematic observations of properties (such as spectra or thermal emission) of

large numbers of known objects. A variety of survey programs are therefore of great potential interest to planetary astronomers. However, these surveys must be designed so as not to exclude moving or variable targets. It is important that planetary astronomers participate in planning future survey programs, and that these programs be operated in such a way that important data on planetary sources are not discarded.

**Interferometry.** Although this report has not identified high-priority new interferometric facilities for the 1990's, we endorse continuing research in this field. Specifically, we support upgrades of the existing millimeter arrays in California (Hat Creek and Owens Valley), which have many research applications in planetary astronomy. Interferometry at many wavelengths is likely to be a central element of astronomical activity in the 2000's, and we must lay the ground work in this decade if the promise of these facilities is to be achieved in the next.

**Laboratory Studies.** The interpretation of data on solar system bodies frequently requires the acquisition and study of new laboratory data. The physical and chemical conditions in cometary comae, in planetary atmospheres, and on planetary surfaces are often outside the range normally studied by chemists, and new laboratory studies at the relevant temperatures, pressures, and radiation environment are needed. Major progress in understanding the chemistry of the interstellar medium, particularly its ice and organic content, is currently being achieved; many of these studies are directly related to the chemistry of the early solar system and those bodies which formed in it. In addition, the chemical and mineralogical *evolution* of the comets, planets, and asteroids can be deciphered with adequate laboratory data and simulations.

**Access to Data.** Astronomical data, often obtained with public funding, lose much of their potential value if not archived and made available to other investigators. Along with an archive, there is need for a catalog of the archive. We encourage efforts to apply new technology and establish uniform standards so that archiving of astronomical data can become routine before the end of the 1990's. In the case of planetary data, such an archive can be made available to the general community through the existing NASA-supported network of Planetary Data Centers.

**Balance between NASA and the NSF.** Planetary astronomy has profited by support from both agencies in the past, and we look forward to continuing this relationship in the future. However, we encourage the two agencies to work more closely together in coordinating their programs. The cost effective use of limited public research funds requires that NASA and the NSF complement, but do not duplicate, each others' programs.

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